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ON THE MONCHIQUTES OR ANALCITE GROUP OF IGNEOUS ROCKS.

As is well known to all petrographers the name of monchiquite was first given by Rosenbusch¹ in 1890 to a series of dark basic dikes occurring in connection with intrusions of eleolite-syenite in Brazil. Similar rocks had been previously known from South Portugal and hence they received their name from the Serra de Monchique.

The material from Brazil was investigated by Hunter and Rosenbusch, and the rocks which have a basaltic habit were found by them to consist of ferro-magnesian minerals in a glass base. The ferro-magnesian minerals were found to be always olivine and pyroxene, while with them were associated sometimes amphibole, sometimes biotite, and sometimes both, and according to these variations the group was subdivided.

Since then these rocks, of slightly varying types, have been found, usually in connection with intrusions of alkali syenites, in various parts of the world. In this country they have been found in Arkansas and in numbers in the Lake Champlain district, and our knowledge of them is chiefly due to the researches of Kemp.²

In all cases the main characteristics of the types described are that the rocks consist of ferro-magnesian minerals, chiefly olivine and pyroxene, lying in what is called a colorless glass base.

The only case in which, so far as we know, this colorless base has been investigated was in the original study by Rosenbusch and Hunter, in which it was separated and analyzed and

¹ Tscher. Min. Mitt., Vol. XI, 1890, p. 445.

² Trap Dikes, Lake Champlain Region; Bull. 107, U. S. G. S., 1893. Igneous Rocks of Arkansas; Ann. Rep. 1890, Vol. II, p. 392 (with J. F. WILLIAMS).

found to consist chiefly of silica, alumina, soda and water. Thus, as Rosenbusch pointed out, it had certain analogies with an eleolite-syenite magma from which the partial magma forming the dikes is supposed to be formed by differentiation of the lime, iron and magnesia. On account of the water it is called a pitchstone glass.

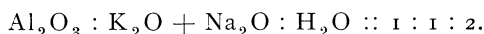
Within the past few years the attention of the author has also been directed to this group of rocks by their occurrence in parts of Montana now being studied in conjunction with Mr. W. H. Weed, under the auspices of the United States Geological Survey. When they first appeared the characterization of them as consisting of ferro-magnesian minerals in a glass base, given by previous authors, was accepted, and one of them so described (in the report on the geology of the Castle Mountain mining district, now passing through the press).

As, however, the number of examples increased and the rocks were studied in connection with their geologic mode of occurrence, it became a source of perplexity as to why such basic magmas, solidifying under the conditions which the general geology of the region evinces, should have formed so much glass.

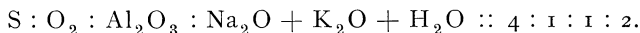
For it must be said that *a priori* one would scarcely expect to find such basic magmas as form the monchiquites, producing glass when solidifying at such depths as they have in the cases which have come under our own observation, and in the instances which have been described by others. This anomaly is all the more marked when the acid dikes and intrusive sheets which so generally accompany them, and which must have been formed under similar conditions, are taken into account. As is well known the acid magmas crystallize with more difficulty than the basic ones; rhyolitic glasses are well known and are common, while tachylites are rare; at the same depths and under the same conditions which cause the very acid magmas to form extremely fine-grained dense or porphyritic rocks the basic magmas crystallize into moderate or even coarse-grained evenly granular ones. If the monchiquites contained so much glass

one would expect all the more to find the acid complementary forms—the oxyphyres—which accompany them also in, at least partly, glassy forms. This, however, is not the case in any of the regions, so far as we know, in which these rocks have been found, where erosion has cut down so as to expose the deeper-seated intrusive types.

The question thus raised on geological grounds concerning the glassy nature of the base was sought to be settled by other means. Since the microscope failed to yield any decisive results, recourse was had to chemical methods. In a number of samples that have been analyzed were some free from biotite and ægirite, and in which consequently all of the alkalis and presumably the alumina and water were in the base. In such cases it is noticed that the molecular ratios of these elements have approximately the relation:



If sufficient silica is deducted to satisfy the lime, iron and magnesia as pyroxene and olivine, the remainder has an approximately molecular relation to the above as follows:



These, however, are the ratios given by the chemical formula of *analcite*. The results, of course, cannot be very accurate, as the exact composition of the crystallized minerals is not known, but are sufficiently close to show that grave doubts must exist concerning the glassy character of the base. Evidently to settle the question the base would have to be separated and analyzed. This has fortunately already been done by Hunter and Rosenbusch in their original investigation, and, as the results to be presently given will show, with great care and skill, on excellent material.

In separating the base from the included minerals by heavy solutions it was found impossible to obtain it absolutely free from microlites of ferro-magnesian minerals, and as Rosenbusch states, a portion of these were attacked by the acid used

in decomposing the substance and went into solution. The analysis by Hunter¹ gave the following results:

| | | |
|--------------------------------|-------|------|
| SiO ₂ | 53.43 | .890 |
| Al ₂ O ₃ | 20.86 | .202 |
| Fe ₂ O ₃ | 2.61 | .016 |
| MgO | .29 | .007 |
| CaO | 1.14 | .020 |
| Na ₂ O | 11.63 | .187 |
| K ₂ O | 2.51 | .026 |
| H ₂ O | 7.06 | .392 |
| | <hr/> | |
| | 99.53 | |

The substance just sank in the heavy liquid with specific gravity of 2.31, and this may be taken as being very close to its own specific gravity.

Of the above analysis about 96 per cent. is made up of silica, alumina, alkalis, and water, the rest is composed of the oxides of the microlites taken into solution. It will be seen that the oxides first mentioned are very close in their molecular ratios, given in the second column, to 4 : 1 : 1 : 2, but a slight excess of silica belonging to the lime, iron, and magnesia is present. The state of oxidation of the iron is uncertain, as it is not mentioned whether ferrous iron was determined or not. If we assume that the lime, iron, and magnesia are present according to the general formula of the amphibole group, RSiO₃, the microlites having been determined as amphibole, and deduct the requisite number of silica molecules to satisfy them, the remainder becomes

| | |
|--------------------------------------|-----------------|
| SiO ₂ | .831 = 4.11 = 4 |
| Al ₂ O ₃ | .202 = 1 = 1 |
| Na ₂ O + K ₂ O | .213 = 1.05 = 1 |
| H ₂ O | .392 = 1.94 = 2 |

The base has therefore the chemical composition Na Al (SiO₃)₂ H₂O, with a little of the soda replaced by potash, or, in other words, it has *the exact chemical composition, the exact specific gravity, the property of gelatinizing with acids, and the optical*

¹Op. cit., p. 454.

properties of analcite, and must therefore be that mineral and not a pitchstone glass, as had formerly been supposed.

The sharpness of the ratios given above is an excellent testimonial to the purity of the material, the care with which it was separated, and to the analytical skill of Hunter.

Thus the supposition that the base of these rocks was very unlikely to be a glass, and the indications previously mentioned that it was analcite, are most strikingly confirmed by these results. It is not to be wondered at that a base of analcite should have been mistaken for a glass by many petrographers, including the author, since, the grains having everywhere the same optical orientation and the same index of refraction, there would be no means of distinguishing them in plain or in polarized light, either from one another or from a continuous isotropic substance like glass. In the original monchiquites from Brazil, specimens and sections of which the author owes to the kindness of Professor Rosenbusch and of Professor A. Lacroix from material collected by Professor O. A. Derby, the analcite often shows a tendency to crystal form by the production of areas which are free from the larger prisms of the ferromagnesian minerals, the latter being arranged around them in wreaths. The areas thus resemble phenocrysts of leucite and they are in reality *phenocrysts of analcite*. They are sprinkled full of the microlites of hornblende described by Rosenbusch, which do not, however, show any tendency to the zonal arrangement shown by such inclusions in leucite.

It is a matter of great interest to recall in this connection that Lindgren¹ only a few months previous to Hunter and Rosenbusch had published an account of certain basaltic dikes occurring in the Highwood Mountains of Montana. They were shown to consist of augite, olivine, iron ore and analcite as phenocrysts in a groundmass of magnetite grains, augite microlites and a second generation of analcite.

The analcite was separated and two analyses were made which are given in I and II.

¹Proc. Cal. Acad. Sci., Series 2, Vol. III, July 1890.

| | I | II | Average | Molec. Ratios |
|--------------------------------|--------|--------|---------|------------------|
| SiO ₂ | 54.90 | 49.87 | 52.38 | .873 |
| Al ₂ O ₃ | 23.30 | 22.55 | 22.92 | .222 |
| Fe ₂ O ₃ | trace | 1.51 | 0.75 | .005 |
| CaO | 1.90 | 2.62 | 2.26 | .040 |
| MgO | 0.70 | 1.28 | 0.99 | .024 |
| Na ₂ O | 10.40 | 10.92 | 10.66 | .171 |
| K ₂ O | 1.60 | 2.66 | 2.13 | .022 |
| H ₂ O | 7.50 | 11.05 | 7.50 | .416 |
| | 100.30 | 102.46 | 99.59 | |

Since the analyses were made on very small quantities the ordinary analytical errors become considerable and it is, therefore, probable that the average of the two would be more correct than either alone. The water in No. II is evidently too high and may be excluded. The average is shown in the third column and its molecular ratios in the fourth. The lime, iron and magnesia are of course due to admixed microlites of pyroxene, and deducting sufficient silica to turn them into the general formula RSiO_3 the remaining ratios have the following relations:

| | | | | | | |
|--------------------------------------|---|---|---|---|---|----------------|
| SiO ₂ | - | - | - | - | - | .799 = 4.1 = 4 |
| Al ₂ O ₃ | - | - | - | - | - | .222 = 1.1 = 1 |
| Na ₂ O + K ₂ O | - | - | - | - | - | .193 = 1.0 = 1 |
| H ₂ O | - | - | - | - | - | .416 = 2.1 = 2 |

which gives the analcite formula $\text{Na Al (SiO}_3)_2 \text{H}_2\text{O}$ with a fair degree of exactness, some of the soda being replaced by a little potash as in the Brazilian rocks.

In his article Lindgren¹ speaks of the difficulty of distinguishing the isotropic analcites from glass and in a review of the paper Iddings² emphasizes this point and suggests that isotropic minerals may have been determined as glass in some cases. It is now becoming evident how often this has, in all probability, been done.

It is now clear from what has been stated above that the

¹Op. cit., p. 55.

²JOURNAL OF GEOLOGY, Vol. I, p. 638.

monchiquites of Rosenbusch and the analcite basalts of Lindgren are the same thing, the only difference being that the Highwood Mountain types are lacking in the amphibole found in the Brazilian ones.

In the Highwood Mountain types, as described by Lindgren, the analcite phenocrysts are sharply idiomorphic, which must have been one factor in preventing Lindgren from falling into the error concerning their nature which so many petrographers have committed. Moreover from this fact it would appear that the Highwood Mountain types are the best crystallized and most individualized type of monchiquites which have yet been described. Rosenbusch indeed classifies them with this group in the last edition of his *Massige Gesteine*.¹

It now seems probable that analcite as a rock component is not limited strictly to the monchiquite group. The base described in basaltic rocks by Bücking² (*Basis zweiter Art*) as a colorless glass containing water, or which is stated to have the general composition of nephelite, that is, consisting of silica, alumina and soda and which gelatinizes readily with acids, is more than probably analcite, and it is quite possible that all of the colorless glasses which have been described as gelatinizing readily with acids have this composition. It seems very unlikely that a glass consisting of silica, alumina and soda would be readily attacked by acids and gelatinize; the basic glasses rich in lime, iron and magnesia and approaching a slag in composition, that is an approximation to the formula R_2SiO_4 , are at times readily dissolved by acids, but it is strongly to be questioned if a soda-alumina glass would be. The determination of a colorless isotropic substance containing silica, water, soda and alumina and which gelatinizes with dilute acids in a rock is as safe a determination of analcite as that of the majority of minerals determined in eruptive rocks.

In the discussion of the primary or secondary nature of the

¹ Third edition, 1895, p. 542-543.

² Basaltische Gesteine, etc., Jahrb. k. k. preuss. geolog. Laudesanst. 1880 and 1881.

analcite in the rocks investigated by him, Lindgren was forced to conclude from the very fresh and unaltered character of the material that it must be of primary origin. The examination of the Highwood rocks by the author confirms this view of Lindgren's. Anyone who has seen the fresh unaltered character of the minerals in these rocks, not only from Montana but from Brazil and from other localities, would find it difficult to explain how the base could have undergone a thorough chemical change and decomposition throughout without the other minerals being affected in the slightest degree and especially the olivine, of all minerals perhaps the one most delicately susceptible to processes of hydration. It actually appears that henceforth we must accept analcite as an important and common rock-forming mineral, almost unquestionably one may say of primary origin. It is understood of course that its occurrence as a secondary mineral also, is not for a moment denied or its importance underrated. It must be said, however, in view of the facts now presented, that many cases where it has been called a secondary mineral are at least doubtful. Many authors for example cite it as secondary after leucite, and one gathers the impression from the context that this is supposed to have happened by weathering; though how leucite, which is a potash compound, is to change into analcite, a soda compound, by the simple addition of water, is not stated. It is true that Lemberg has shown that leucite is changed into analcite by the action of soda solutions; but, as in the case of the monchiquites, it can hardly be supposed that such an action could have taken place without altering the other minerals, and it would be difficult to see where so great a quantity of soda, as would be required, could have come from. It is also difficult to see how it could have formed from nephelite, norian or sodalite without the formation of other secondary products as noted above.

Lindgren¹ suggests that the mineral could have formed from igneous magmas, provided that the magma contained water and crystallized under sufficient pressure to retain it, and cites the

¹Op. cit., p. 52.

presence of water in undoubted pitchstone glasses as a proof that water may be retained by igneous magmas at high temperatures. We believe this explanation to be the correct one and will present some further proofs of its probability.

The intimate relation between biotite on the one hand and olivine and leucite or orthoclase on the other was pointed out by Iddings¹ and has been further discussed by Bäckström² and the author.³ Iddings and Bäckström point out that since for the production of biotite certain mineralizing agents, such as water and fluorine, are necessary, since they enter into its composition, the biotite rich rocks must be intrusive ones, whereas if the magma attains the surface and under the diminished pressure the water escapes, then olivine and leucite may be produced. By this is explained the general absence of leucite in abyssal rocks and its frequency in extrusive lavas. This process would of course find its most natural expression in magmas rich in magnesia and potash.

When we consider the magmas in which soda predominates however, it is clear that quite different processes will take place. There is no such relation between soda and magnesia as is shown by potash and magnesia in the biotite molecule. Therefore we might expect that if the magma contained water vapor and soda predominated in it, that analcite would be formed if the magma crystallized under pressure with considerable rapidity, whereas if the magma were anhydrous or the water vapor could escape without taking part in the crystallization either by relief of pressure or by very slow and gradual processes of crystallization, which would exclude it, then we should expect nephelite to form or nephelite and the albite molecule, the latter, perhaps, giving rise to plagioclase.

From this it would follow that the conditions most favorable for the production of primary analcitic rocks would be in dikes and small intrusions which is in fact the place where they occur,

¹ *Origin Igneous Rocks*, Bull. Phil. Soc., Washington, Vol. XII, p. 176, 1892.

² *Geol. Fören. Förh.*, Stockholm, Vol. XVIII, p. 161, *seq.*, 1896.

³ *Highwood Mts. Bull. Geol. Soc. Am.*, Vol. VI, p. 409, 1895.

while the larger bodies of magma would tend to form theralites, ijolites, etc., and the surface lavas would appear as nephelite tephrites, basanites, basalts, nephelinites, etc.

As a corollary of this it would follow that all of these rocks should possess a general similarity of chemical composition, which in fact they do, as may be seen from the following table of analyses:

| | I | II | III | IV | V | VI | VII | VIII | IX |
|--------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| SiO ₂ | 46.48 | 43.74 | 43.50 | 43.85 | 43.17 | 51.03 | 44.85 | 42.12 | 42.88 |
| Al ₂ O ₃ | 16.16 | 14.82 | 18.06 | 15.25 | 15.24 | 8.48 | 18.08 | 14.35 | 13.99 |
| Fe ₂ O ₃ | 6.17 | 2.40 | 7.52 | 7.63 | 7.61 | 11.95 | 7.71 | 13.12 | 15.72 |
| FeO | 6.09 | 7.52 | 7.64 | 4.57 | 2.67 | 3.21 | 3.23 | | |
| MgO | 4.02 | 6.98 | 3.47 | 4.47 | 5.81 | 6.34 | 4.16 | 6.14 | 3.94 |
| CaO | 7.35 | 10.81 | 13.39 | 8.54 | 10.63 | 6.96 | 9.97 | 13.00 | 12.64 |
| Na ₂ O | 5.85 | 3.08 | 2.00 | 4.22 | 5.68 | 5.42 | 3.19 | 4.11 | 4.73 |
| K ₂ O | 3.08 | 2.90 | 1.30 | 4.04 | 4.07 | 4.83 | 2.82 | 2.18 | 3.96 |
| H ₂ O | 4.27 | 2.94 | 1.22 | 1.80 | 3.57 | 1.68 | 2.56 | 3.42 | 3.08 |

- I Monchiquite, Brazil (Hunter and Rosenbusch *op. cit.*), Hunter anal.
 II Monchiquite, Brazil (Hunter and Rosenbusch *op. cit.*), P. Jannasch anal.
 III Monchiquite, Magnet Cove, Ark. (Williams Igneous Rocks, Ark., 1890, p. 295), W. A. Noyes anal.
 IV Monchiquite-Camptonite, Bohemia (Hibsch Tscher. Mitt. XIV, 1894, p. 101), F. Hanusch anal.
 V Theralite, Crazy Mts., Montana (Wolff Petrog. Crazy Mts., 1885), J. E. Wolff anal.
 VI Theralite, Crazy Mts., Montana (Wolff Petrog. Crazy Mts., 1885), A. M. Comey anal.
 VII Nephelite tephrite, Bohemia (Hibsch *op. cit.*, p. 109), F. Pfohl anal.
 VIII Nephelite basalt, Löbauer Berg, Heidepriem (Zirkel Petrog., 2d ed., Vol. III, p. 37).
 IX Nephelinite, Laach., Eifel, vom Rath (Zirkel Petrog., 2d ed., Vol. III, p. 61).

The list might be greatly extended but the above are sufficient to show that the magmas producing these rocks have certain chemical characteristics in common, low silica, moderate alumina and alkalis with soda predominating over potash, and high lime, and iron, and high to moderate magnesia.

In this connection the author cannot refrain from pausing a moment to call the attention of petrographers to the fact, apparently not often recognized, that analyses of basic rocks, rich in

ferro-magnesian minerals, are very often vitiated by a failure to properly separate alumina from magnesia. Many analyses which would otherwise be good are spoiled by this error. The writer's attention has been strongly called to this point on examining, in connection with this article, various analyses of basic rocks. The types are described as consisting chiefly or largely of pyroxene with or without olivine and with the felspathoid components in perhaps subordinate quantity, yet the analyses may show very high alumina with very little magnesia. An example might be quoted of an analysis of this class published within the last few years :

| SiO ₂ | Fe ₂ O ₃ ,FeO | Al ₂ O ₃ | CaO | MgO | K ₂ O | Na ₂ O | P ₂ O ₅ | Ign. |
|------------------|-------------------------------------|--------------------------------|------|------|------------------|-------------------|-------------------------------|--------------|
| 47.83 | 4.57 | 30.28 | 6.72 | 4.32 | trace | 1.30 | 2.19 | 2.05 = 99.26 |

In the light of our present knowledge this may almost be said to be an impossible composition for an igneous rock, and it is very clear that a large part of the magnesia must have been thrown down with the alumina. The tendency of alumina to drag down magnesia on precipitation with ammonia is very great and only to be prevented by the presence of a liberal quantity of ammonium salts, and the precipitation should always be repeated, especially where both oxides are present in considerable quantities, under which circumstances even a third precipitation may be necessary. There are many excellent chemists who, from a lack of experience in silicate analysis, fail properly to appreciate this point, and it has been perhaps the most common error in rock analyses.

Returning to our analcite rocks, it is of interest to observe in this connection that leucite and analcite have the same crystal form and the same structural formula except the addition of the molecule of water in the analcite; it is not strange that this difference between them should exist when one reflects how commonly soda salts contain water of crystallization and how much more rarely the potash compounds assume it.

The result of this is then to show why leucitic rocks are commonly effusive ones while the analcitic rocks would be more

commonly intrusive ones, though it is clear special cases might arise where the reverse was the case. Thus Cross¹ is inclined to view the analcite in phonolites described by him as of primary origin and the latest component to form, its formation being due to the local concentration of aqueous vapor produced by its exclusion where crystallization was progressing and by its accumulation in other spots.

The literature contains abundant references to the occurrence of analcite in igneous rocks, but in the great majority of them the rocks described are altered and unlike the beautifully fresh types whose discussion has served for the basis of this article, and it must therefore be uncertain whether the analcite is of primary or secondary origin. In some cases it would appear to be primary, but a discussion of them would carry us too far.

It is now clear (whether one accepts the primary origin of analcite or not) that we must recognize the analcite group of rocks just as we have the leucite group. The analcite basalts corresponding to the leucite basalts are the *Monchiquites* of Rosenbusch, the analcites or olivine free analcite basalts are the *Fourchites* of J. Francis Williams.² The demonstration that the base of the monchiquite group is not glass but analcite does not in any sense impair its distinctness and individuality as a rock group, on the contrary it strengthens it by giving a definiteness of mineral composition that it did not before possess, and at the same time clears up what was one of the most puzzling questions in the petrography of igneous rocks occurring in these small intrusive masses.

And in conclusion we note also that the present case presents another example of how magmas, possessing similar chemical compositions, may form different mineralogical products when crystallizing under different physical conditions.

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New Haven, May 1896.

¹ Geology Cripple Creek, XVI, Ann. Rep. U. S. G. S., Pt. II, p. 36, 1895.

² Igneous Rocks, Ark., p. 110, 1890.